

Jets and QSO Spectra

Beverley J. Wills and M. S. Brotherton

Department of Astronomy, University of Texas at Austin, Texas, 78712

Abstract. QSOs' emission lines arise from highest velocity ($\sim 10^4 \text{ km s}^{-1}$), dense gas within ~ 0.1 parsec of the central engine, out to low-velocity, low-density gas at great distances from the host galaxy. In radio-loud QSOs there are clear indications that the distribution and kinematics of emission-line gas are related to the symmetry axis of the central engine, as defined by the radio jet. These jets originate at nuclear distances < 0.1 pc — similar to the highest-velocity emission line gas. There are two ways we can investigate the different environments of radio-loud and radio-quiet QSOs, i.e., those with and without powerful radio jets. One is to look for optical-UV spectroscopic differences between radio-loud and radio-quiet QSOs. The other is to investigate dependences of spectroscopic properties on properties of the powerful jets in radio-loud QSOs. Here we summarize the spectroscopic differences between the two classes, and present known dependences of spectra on radio core-dominance, which we interpret as dependences on the angle of the central engine to the line-of-sight. We speculate on what some of the differences may mean.

1 Introduction

The optical-ultraviolet emission-line profiles and intensity ratios are remarkably similar for radio-loud QSOs (RLQs) and radio-quiet QSOs¹ (RQQs), for a wide range of luminosities (Baldwin et al. 1995). The broad emission lines arise predominantly by photoionization of the broad-line region (BLR), a region of dense gas within ~ 0.1 parsec of the central engine. Lower velocity ($\sim 500 \text{ km s}^{-1}$) gas of the narrow-line region (NLR) arises at distances from parsecs to kiloparsecs. The BLR and NLR are not single, homogeneous regions: the highest-velocity, highest-density gas ($\sim 10^{12-13} \text{ cm}^{-3}$) — the very broad line region (VBLR) — occurs closest to the central engine and produces the broadest emission lines ($\sim 10^4 \text{ km s}^{-1}$). These are typically blueshifted by $\sim 1000 \text{ km s}^{-1}$ with respect to the systemic (NLR) redshift. Gas of the ILR — intermediate in velocity, density, and distance, between the VBLR and NLR — produces profiles of $\sim 2000 \text{ km s}^{-1}$ width. Much of the diversity in line ratios and profiles can be reproduced by a combination of spectra from the VBLR, ILR and NLR (Brotherton et al. 1994b).

¹ 'QSO' refers to all luminous AGN ($L \gtrsim 10^{11} L_{\odot}$, $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$). A radio-loud QSO is one having $F_{5\text{GHz}}/F_{4400} \gtrsim 10$, where F is the rest frame flux-density in mJy. Such strong radio emission is assumed to indicate powerful radio jets. For a short 'course' on emission lines, see Netzer (1990), and reviews to appear in the Proceedings of IAU Colloquium No. 159, '*Emission Lines in Active Galaxies*' (Shanghai, 1996).

The powerful, synchrotron-emitting radio jets arise within VBLR distances, and often extend hundreds of Kpc from the nucleus. Thus, differences in the optical-ultraviolet spectra of the BLR between the RLQs with powerful jets, and the RQQs of 1000 – 10,000 less radio luminosity, should give clues to differences in material that fuels or is expelled by the central engine, and how this might be related to the formation and collimation of the jets. Differences in the optical-ultraviolet spectra of the lower-speed gas might reflect jet interaction with material in the inner regions of the host galaxy, up to many Kpc distant — by means of entrainment, shock excitation, and photoionization by beamed high-energy synchrotron emission.

The spin axis of the central engine is indicated by the position angle of the base of the jet, and by the radio core dominance that indicates the angle of the jet to the line-of-sight (see the chapter, ‘Accretion and Jet Power’). Thus dependence of spectral properties on core dominance provides a statistical way to investigate axisymmetric structure of the gaseous environment in RLQs, necessary for the interpretation of radio-loud – radio-quiet differences.

First we summarize spectroscopic differences between RLQs and RQQs, then summarize some spectroscopic dependences on radio core-dominance. We suggest a picture for future testing, which is consistent with the present observations.

2 Radio-loud – Radio-quiet Spectroscopic Differences

Despite the great similarity of RLQ and RQQ spectra, differences are being recognized as a result of improved data over a wide spectral range, for appropriate samples of QSOs. We present results that derive from our own and other investigations, using ground-based spectrophotometry in the optical-infrared, and ultraviolet spectroscopy with the Hubble Space Telescope, emphasizing those that are most simply interpreted without detailed statistical analysis. Even the strongest relations involve more than two variables, and multivariate analyses of carefully defined samples are needed. Some of this work is in progress.

2.1 The Fe II – [O III] Relation

One of the strongest correlations is the inverse correlation between the strength of blended optical Fe II emission (between $H\gamma$ and $H\beta$, and 5150 – 5300 Å), and the strength of [O III] $\lambda 5007$ — the strongest optical line from the NLR. This was nicely presented by Boroson & Green (BG, 1992) for Seyfert 1 galaxies and QSOs from the PG survey — a predominantly radio-quiet sample. Fig. 1 illustrates typical spectra of the $H\beta$ region, and in Fig. 2, the inverse relation is shown by comparing equivalent widths, including BG data for RQQs (open symbols), but adding data for RLQs from the investigation by Brotherton (1995; filled circles). Two blazars were excluded, because of

their strong, variable synchrotron continua. The samples cover comparable optical luminosities. There is a striking difference between the RLQs and RQQs: the RLQs appear clustered towards the weak-Fe II, strong-[O III] end of the relation.

Fig. 1. The $H\beta$ -[O III] $\lambda 5007$ region in a typical radio-loud and typical radio-quiet QSO. For the radio-quiet QSO, Fe II blends contribute at all wavelengths in this region, and [O III] $\lambda 5007$ is barely visible. For the radio-loud QSO Fe II blends are weaker, and stronger NLR emission of [O III] $\lambda 5007$ and [O III] $\lambda 4363$ is present.

The [O III] is representative of NLR emission. The strong optical Fe II emission must arise in regions of high density and high optical depth to the ionizing continuum, and the line widths of blended Fe II appear to be similar to other broad lines, suggesting an origin in the BLR. However, problems in explaining the great strength of Fe II optical emission have led to suggestions of a different source of excitation from the standard ultraviolet lines ($\text{Ly } \alpha$, C IV $\lambda 1549$, C III] $\lambda 1909$). This problem is probably related to the general ‘energy budget’ problem, where the observed ultraviolet continuum does not appear strong enough, in general, to produce the strengths of low ionization lines. Assuming that the Fe II emission does in fact arise in the BLR, the inverse correlation can be explained by object-to-object differences in covering of the ionizing continuum by the BLR gas. The greater the BLR covering, the greater is the shielding of the more distant NLR from ionizing photons — a possibility also considered, but fleetingly, by BG.

Fig. 2. (left) The equivalent width of [O III] $\lambda 5007$ vs. the equivalent width of optical Fe II. Open circles are for RQQs from BG, filled circles for RLQs (Brotherton 1995), open triangles for high-ionization BAL QSOs, and stars for low-ionization BAL QSOs. Upper limits for EW[Fe II] are 1.5σ ; for EW [O III], 3σ .

Fig. 3. (right) The EW of [O III] $\lambda 5007$ vs. the width (FWHM) of the C III] $\lambda 1909$ feature. Data are from Brotherton (1996). The symbols are the same as for Fig. 2.

2.2 Broad Absorption Lines and Associated Absorption

Broad absorption lines (BALs) — troughs of absorption extending between $\sim 5,000 \text{ km s}^{-1}$ and $25,000 \text{ km s}^{-1}$ blueward of the corresponding emission line peak — are recognizable in $\sim 10\%$ of QSOs, but have never been seen in RLQs (Stocke et al. 1992). Associated absorption is narrow, intrinsic absorption occurring near (within a few hundred km s^{-1}) or blueward of the emission line peak. Associated absorption is common in BAL QSOs and occurs in other RQQs. It is also common in RLQs — probably occurring more often in lobe-dominated RLQs. Two classes of BAL QSO are distinguished — high-ionization BAL QSOs with C IV, N V and Ly α BALs, and low-ionization BAL QSOs, which show, in addition to the high-ionization BALs, BALs of Mg II, Al III, and probably Fe II and Na I. Under current debate is the hypothesis that BAL QSOs and other RQQs are the same — the observed difference depending on whether or not intrinsic broad absorbers happen to lie along our line-of-sight to the nucleus. This hypothesis receives strong support from the

general similarity of their broad-emission-line ultraviolet spectra (Weymann et al. 1991).

However, low-ionization BAL QSOs do show some other spectral differences. One of these is illustrated in Fig. 2 (stars and open triangles represent low- and high-ionization BAL QSOs, including one [O III] $\lambda 5007$ upper limit) — nearly all the low-ionization BAL QSOs have very weak [O III] and are super-Fe II emitters. Nearly all known low-ionization BAL QSOs show significant scattering polarization and significantly reddened continua. The PG QSOs are selected by UV-excess and are therefore biased against being dust-reddened; however, many QSOs selected by high infrared luminosity (the IRAS ultraluminous QSOs) show high scattering polarization and reddened continua — and a significant fraction show low-ionization BALs (based on small numbers, as yet), and/or belong to the rare class of super-Fe II emitters. The strong Fe II is also significantly associated with narrow $H\beta$ from the BLR, and softer X-ray spectra (0.3 – 2 keV) (Laor et al. 1994, for PG QSOs; Boller et al. 1995, & Grupe et al. 1995, for soft X-ray ROSAT AGN). The polarization, reddening, and BALs can be understood as line-of-sight effects; the Fe II emission, $H\beta$ width and X-ray slope are not as simply interpreted. We therefore do not suggest that the entire [O III]–Fe II anticorrelation is a line-of-sight effect; there is probably more than one physical cause.

Recently BALs and narrower associated absorption have been linked with both warm and cool X-ray edge absorption, placing the absorbing material within or just beyond BLR distances from the nucleus (e.g. Mathur et al. 1995).

2.3 Stronger ILR emission in Quasars?

Fig. 2 shows that radio-loud QSOs tend to have stronger emission from the NLR compared with the BLR. The cause may be related to the alignment between jets and extended narrow-line emission, resolved on scales of kpc, and between radio power and the strength and width of [O III] emission in radio galaxies (e.g. Baum & Heckman 1989; Whittle 1992). Narrower, but stronger, BLR lines of C IV $\lambda 1549$ and C III] $\lambda 1909$ in RLQs compared with RQQs suggest a greater contribution from ILR gas (Brotherton et al. 1994a; Francis et al. 1993), and this is further supported by a link between the ILR and NLR gas, being investigated by Brotherton (1996), and illustrated by the inverse correlation between [O III] strength and C III] $\lambda 1909$ width (Fig. 3).

Hypotheses to explain the enhanced emission from lower-velocity gas in RLQs include jet-shocked gas, jet-induced star-formation, and ionization by beamed ultraviolet synchrotron emission.

2.4 BLR Line Asymmetries

There are significant statistical differences in line profiles:

- C III] $\lambda 1909$ and C IV $\lambda 1549$ are narrower in RLQs than in RQQs.
- The C IV line generally has stronger red than blue wings in RLQs, but the blue wing is often stronger than the red in RQQs (Wills et al. 1993, 1995).
- The H β broad line also often has stronger red wings in RLQs, with the RQQs showing similar frequency of red and blue asymmetries (e.g. Sulentic 1989, Corbin 1993; BG92).

Systematic line asymmetries imply radially flowing gas with obscuration. The most likely obscuration related to the emission-line region seems to be either dust within the unilluminated backside of gas clouds, or an emission region within an obscuring torus. In these cases the above line asymmetries suggest that RQQs, and perhaps all QSOs, have greatest inflow in the innermost BLR, but that in RLQs, additional outflow occurs, often producing redshifted line wings.

Another likely contributor to some line asymmetries is blending by other emission lines, for example, Fe II in the red wing of C IV $\lambda 1549$. In some QSOs with strong Fe II emission or BALs, the $\lambda 1909$ feature is dominated by blended Fe III emission (Hartig & Baldwin 1986; Baldwin et al. 1996), and may well account for the larger width of this ‘C III]’ feature in RQQs.

3 Radio Core-dominance Relationships for RLQs

The previous chapter (Accretion and Jet Power) presented evidence that, for RLQs, core-dominance is a measure of orientation of the jet axis to the line-of-sight, and we retain that interpretation here.

3.1 Line Widths & Asymmetries

The width of the broad H β line (FWHM) is inversely correlated with core-dominance and we have suggested that this is the result of viewing predominantly planar motions that are perpendicular to the jet axis: in core-dominated RLQs the radial velocities are smaller, in lobe-dominated RLQs, up to $\sim 8,000 \text{ km s}^{-1}$, and in broad-line radio galaxies where we may be viewing the central QSO at even higher inclination, widths up to $\sim 20,000 \text{ km s}^{-1}$ are found (Wills & Browne 1986; Wills & Brotherton 1995; see also the previous chapter, *Accretion and Jet Power*). This dependence is weaker for the C IV $\lambda 1549$ line, which has a greater contribution from ILR gas than does H β (Brotherton 1995).

Core-dominated RLQs have stronger red wings for C IV $\lambda 1549$ (Wills et al. 1995; see Barthel, Tytler & Thomson 1990). For a higher-redshift sample, Corbin (1991) found a trend in the opposite sense, but this was a marginal result. On the other hand, for H β , it is the lobe-dominated RLQs that often show strong red wings (e.g. Fig. 1; BG; Brotherton 1996). For examples of H β

line asymmetries, see Fig. 6 in BG. Again, line asymmetries imply radial flow plus obscuration, so these correlations suggest axial flow of high-ionization gas, and radial flow of low-ionization gas in a plane perpendicular to the jet axis.

3.2 Associated Absorption and Reddening

Excluding from consideration those core-dominant RLQs (blazars) with steep, beamed IR – ultraviolet synchrotron continua, there is a strong trend for the most lobe-dominant sources to show steeper optical-ultraviolet continua. This has been seen for the 3CR sample (see the lobe-dominated sources in Smith & Spinrad 1980), especially when the broad-lined radio galaxies are included, and is shown more quantitatively for the 408 MHz Molonglo Quasar Sample (Baker & Hunstead 1995). Baker & Hunstead find the same reddening trend in the Balmer decrements.

There is a corresponding trend for increased numbers of associated absorption systems in lobe-dominated RLQs (Aldcroft et al. 1994, Wills et al. 1995).

All these trends suggest increasing concentrations of low-ionization material at the largest angles to the jet axis, some of which must be close to the active nucleus (see X-ray absorption results, §2.2).

3.3 Fe II and [O III] Emission

The larger $\text{Fe II}(\text{optical})/[\text{O III}]$ and $\text{H}\beta/[\text{O III}]$ ratios are seen in the most core-dominated RLQs (Jackson & Browne 1991), and the ultraviolet ‘Little Blue Bump’, composed of blended Fe II emission and Balmer continuum, shows the same trend in the Molonglo Quasar Sample (Baker & Hunstead 1995). Jackson and Browne interpreted this trend in terms of axisymmetric Fe II line emission. Perhaps the Fe II-emitting region occurs near the inner edge of a dusty torus and is therefore shielded from the observer more readily at higher inclination angles than other broad lines produced nearer the center.

The stronger red wings on the C IV line for core-dominated RLQs, mentioned above, could be low-optical-depth ultraviolet Fe II emission, related to the greater strength of Fe II (optical) in core-dominated RLQs.

4 Summary and Discussion

Despite the great similarity between the spectra of RLQs and RQQs, the following observational differences are statistically very significant:

In RLQs lower-velocity (NLR, ILR) emission lines are more prominent, and C IV and $\text{H}\beta$ emission lines are asymmetric with stronger red wings. While there is a wide dispersion in properties, RQQs have, on average, stronger

Fe II emission, and $\sim 10\%$ show strong, broad-absorption troughs of high- and low-ionization gas – a phenomenon that is apparently unique to RQQs.

Two apparently independent relations account for much of the diversity in the optical-ultraviolet spectra:

- (i) For RLQs, with increasing core-dominance, emission lines are narrower, Fe II emission is stronger, and C IV more often has stronger red wings. With decreasing core-dominance, H β more often has stronger red wings, and the likelihood of associated absorption and reddening increases.
- (ii) For RQQs, there is an inverse relation between the strengths of Fe II and [O III] $\lambda 5007$ emission, with the strong-Fe II–weak [O III] QSOs being associated with low-ionization BALs, reddening and polarization.

We note that the properties accounting for the radio-loud – radio-quiet differences are those involved in these two relations.

If we interpret line profiles as velocity profiles (rather than as blended emission), and assume dust exists on the unilluminated sides of photoionized gas regions and in a torus, then we can interpret the observations as follows: For RLQs, increasing radio core-dominance means smaller inclination of the rotation axis to the line-of-sight. Kinematics, line emission, and the distribution of dust and absorbing gas are axisymmetric. Broader emission lines at higher inclinations means greater velocities in a plane perpendicular to the axis. Red wings on C IV for core-dominant RLQs imply high-ionization axial outflow, and red wings on H β for lobe-dominated RLQs imply lower-ionization planar outflow. At higher inclinations (edge-on view), high-density, low-ionization Fe II-emitting gas, being located at the inner edge of the purported dusty torus, is partially shielded from view, and the line-of-sight to the nucleus is more likely to pass through dust and outflowing associated absorbers. Perhaps Fe II-rich grains, having the highest evaporation temperatures, exist at the inner edge of the torus, producing Fe II-rich gas.

Comparison with the profiles of RQQs suggests that the outflow of emission-line gas is unique to RLQs. Blueshifted VBLR emission seen in C IV in RQQ may be common to all QSOs (in RLQs, this is difficult to determine because of the presence of stronger red wings), indicating higher-ionization, higher-velocity inflowing gas closer to the central engine. This inflow may be related to accretion.

It has not been determined whether distribution of nuclear gas in luminous RQQs is symmetric about a rotation axis, although the existence of several examples of alignment between weak radio structure and ionization cones in some quite luminous Seyfert galaxies suggests that this might be the case (NGC 1068, Antonucci 1993). BAL material does in some instances cover less than 4π sr, so the appearance of BAL QSOs must depend on orientation. It would be important to understand whether the distribution of BAL gas is related to any structure axis.

What underlies the Fe II – [O III] anti-correlation? We suggested that decreasing covering of the ionizing continuum by dense, thick, Fe II-emitting

gas could simultaneously reduce Fe II emission and allow escaping photons to ionize lower-density, more-distant gas, increasing [O III] emission. The characteristics of line-of-sight dusty material and low-ionization high-velocity out-flowing BAL gas dominate increasingly with increasing Fe II and decreasing NLR ([O III]) strengths. If all RQQs have BALs then orientation is important in determining BAL characteristics. If this relation were one of orientation, then the different locations of RLQs and RQQs in Fig. 2 would require them to be intrinsically different. In the next chapter we suggest ways in which the inner-galaxy environment may explain the observed radio-loud – radio-quiet differences.

References

- Aldcroft, T., Bechtold, J., Elvis, M. (1994): Mg II Absorption in a Sample of 56 Steep-Spectrum Quasars. *ApJS* **93**, 1
- Antonucci, R. R. J. (1993): Unified Models for Active Galactic Nuclei and Quasars *ARAA* **31**, 473–521
- Baker, J. C., Hunstead, R. W. (1995): Revealing the Effects of Orientation in Composite Quasar Spectra. *ApJL* **452**, L95–L98
- Baldwin, J. A., Ferland, G. J., Korista, K., Verner, D. (1995): Locally Optimally Emitting Clouds and the Origin of Quasar Emission Lines. *ApJ* **455**, 119
- Baldwin, J. A., Ferland, G. J., Carswell, R. F., Phillips, M. M., Wilkes, B. J., Williams, R. E. (1996): in preparation. *ApJ* **000**, 000
- Barthel, P. B., Tytler, D. R., Thomson, B. (1990): Optical Spectra of Distant Radio Loud Quasars. I - Data: Spectra of 67 Quasars. *AAS* **82**, 339
- Baum, S. A., Heckman, T. (1989): Extended optical line emitting gas in powerful radio galaxies - What is the radio emission-line connection? *ApJ* **336**, 702
- Boller, T., Brandt, W. N., Fink, H. (1995): Soft X-ray Properties of Narrow-Line Setfert 1 Galaxies. *AA*, in press
- Boroson, T. A., Green, R. F. (1992): The Emission Line Properties of Low-redshift Quasi-Stellar Objects. *ApJS* **80**, 109–135 (BG)
- Brotherton, M. S., Wills, B. J., Steidel, C. C., Sargent, W. L. W. (1994a): Statistics of QSO Broad Emission Line Profiles. II. The C IV $\lambda 1549$, C III] $\lambda 1909$, and Mg II $\lambda 2798$ Lines. *ApJ* **423**, 131–142
- Brotherton, M. S., Wills, B. J., Francis, P. J., Steidel, C. C. (1994b): The Intermediate Line Region of QSOs. *ApJ* **430**, 495–504
- Brotherton, M. S. (1995): The Profiles of H β and [O III] $\lambda 5007$ in Radio-Loud Quasars. *ApJ*, in press
- Brotherton, M. S. (1996): A Comparison of H β and [O III] $\lambda 5007$ in Radio-Loud and Radio-Quiet QSOs. *ApJ*, to be submitted
- Corbin, M. R. (1991): The Emission Line Properties of Steep Radio Spectrum Quasars. *ApJ* **375**, 503–516
- Corbin, M. R. (1993): On the Relation of the X-ray and Emission Line Properties of Low-redshift QSOs. *ApJ* **403**, L9–L11
- Francis, P. J., Hooper, E. J., Impey, C. D. (1993): The Ultraviolet Spectra of Radio-Loud and Radio-Quiet Quasars. *AJ* **106**, 417

- Grupe, D., Beuermann, K., Mannheim, K., Reinsch, K., Thomas, H.-C., Fink, H. H. (1995): Properties of Bright Soft X-ray-Selected ROSAT AGN. AA, in preparation
- Hartig, G. F., Baldwin, J. A. (1986): The Emission-line Regions in Broad Absorption Line Quasars. *ApJ* **302**, 64
- Jackson, N., Browne, I. W. A. (1991): Optical Properties of Quasars. II - Emission-line Geometry and Radio Properties. *MNRAS* **250**, 422
- Laor, A., Fiore, F., Elvis, M., Wilkes, B. J., McDowell, J. C. (1994): The Soft X-ray Properties of a Complete Sample of Optically Selected Quasars. 1: First Results. *ApJ* **435**, 611
- Mathur, S., Elvis, M., Singh, K. P. (1995): Strong X-Ray Absorption in a Broad Absorption Line Quasar: PHL 5200. *ApJ* **455**, 9
- Netzer, H. (1990): AGN Emission Lines. in *Active Galactic Nuclei*, eds. T. J.-L. Courvoisier & M. Mayor (Springer-Verlag: Heidelberg)
- Smith, H. E., Spinrad, H. (1980): Spectrophotometry of Faint, red 3C QSO Candidates. *ApJ* **236**, 419
- Stoeck, J.T., Morris, S. L., Weymann, R. J., Foltz, C.B. (1992): The radio properties of the Broad Absorption Line QSOs. *ApJ* 396, 487–503
- Sulentic, J. W. (1989): Toward a Classification Scheme for Broad-Line Profiles in Active Galactic Nuclei. *ApJ* **343**, 54
- Weymann, R. J., Morris, S. L., Foltz, C. B., Hewett, P. C. (1991): Comparisons of the Emission-line and Continuum Properties of Broad Absorption Line and Normal Quasi-Stellar Objects. *ApJ* 373, 23–53
- Whittle, M. (1992): Virial and Jet-induced Velocities in Seyfert Galaxies. III. Galaxy Luminosity as Virial Parameter. *ApJ* **387**, 121
- Wills, B. J., Brotherton, M. S., Fang, D., Steidel, C. C., Sargent, W. L. W. (1993): Statistics of QSO Broad Emission-Line Profiles. I. The C IV $\lambda 1549$ Line and the $\lambda 1400$ Feature. *ApJ* **415**, 563–579
- Wills B. J., Brotherton M. S. (1995): An Improved Measure of Quasar Orientation. *ApJ* **448**, L81–L84
- Wills B. J., Browne, I. W. A. (1986): Relativistic Beaming and Quasar Emission Lines. *ApJ* **302**, 56
- Wills B. J., Thompson, K. L., Han, M., Netzer, H., Wills, D., Baldwin, J. A., Ferland, G. J. Browne, I. W. A., Brotherton M. S. (1995): Hubble Space Telescope Sample of Radio-loud Quasars: Ultraviolet Spectra of the First 31 Quasars. *ApJ* **447**, 139



